PM fractional machines adopting bonded magnets: effect of different magnetizations on the energetic performance

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***Abstract* – The adoption of Permanent Magnets in small brushless machines for automotive applications is becoming frequent. Some research on bonded magnets is being carried on to substitute the ferrites. In the paper the parallel and radial magnetizations are considered: the different process complexity levels are analyzed and the effects on the iron losses and the energetic performances are evaluated by means of a simulation analysis and its experimental validation.**

***Index Terms* – Fractional PM machines, magnetization patterns, magnetization process, parallel and radial magnetization, hysteresis and eddy currents losses, energetic performance.**

I. Introduction

The use of Permanent Magnets (PM) is increasing especially for fractional motors used for adjustable speed drives. For instance, among the applications of the automotive world where electric motors are required [1], [2], [3], the cooling systems with fans driven by small brushless motors are widely used.

They are normally small machines with internal stator, dummy slots and outrunner rotor with Permanent Magnets; an example that has been considered for the present work is shown in Fig. 1.

Moreover the considered motor structure is becoming very popular [4] and it seemed a good choice to select such a motor type as a reference case for quantitative analysis and experimental activity in the ambit of the research activity concerning the realization and application of new magnet types.

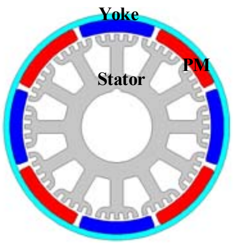

Fig. 1 – Brushless motor under exam

In the past activity a deep interest of the Authors has been addressed to new molding solutions [5], [6].

But a subject which constitutes object of technical debate concerns the type of the possible magnetization process [7], [8], [9], [10]; in this work a comparison will be carried out about the motor performances related to the two main types of magnet magnetization: parallel and radial [11], [12], [13], [14] [15], as it has already been done for the case of ferrite magnets.

The comparison is here performed under the point of view of the effect of the selected magnetization technique [10], on the potential transformed electromechanical power and to related energetic aspects [16], [17]. The justification of the attention for the argument is related to the strong differences in the magnetization process between the two solutions, under both technical and economic point of view. That is especially important for the case of low cost and mass production motors [1], [18] as the one that is here considered.

The adoption of bonded magnets [19] aims at increasing the flux with respect to ferrites [20], [21] and can represent a good economic compromise with respect to sintered magnets [22], [23].

The most convenient and interesting solution should be the direct substitution into machines already under production; anyway the hypothesis of proceeding in such a way (that is here considered and experimented) can give useful information about the energetic effects of such approach.

Under such a point of view the reported analysis provides the evaluation of the different quantities useful for an energetic comparison of the obtainable performances. At the aim, also the conventional input and output power values will be calculated, for two different motor prototypes.

II. Materials and Magnetization Processes

The authors' main goal is the evaluation of the potential benefits coming from the substitution of the anisotropic ferrite magnets with bonded ones [5], [6], [20] and the influence of the magnetization direction on the losses in the machine.

The first operating step has been the production of magnets with the required shape and geometry, and of magnetic samples (having the same composition and obtained with the same production parameters) for the necessary magnetic characterization.

The realized mixture adopted as base powder, NdFeB isotropic powder MQP14-12 (B_r = 850 mT, $(B \times H)_{max}$ = 120 kJ/m^3, H_{cj} = 1050 kA/m, specific for high temperature applications) [24], [25] and phenolic resin as filler; the base powder is used without any previous treatment and mixed with mono-component phenolic resin (3.3% in weight and about 22% in volume of resin).

The following process parameters have been adopted: pressure on the powder in the mould: 160 MPa @ 150 °C, no thermal treatment.

The motor considered in the present activity is equipped with bonded magnets [11], whose magnetic data are reported in the following Table I, together with the original ferrite characteristics.

Type of magnets		Anisotropic ferrite	Phenolic NdFeB
Remanence	B_r [T]	0.420	0.541
Coercivity	H_c [kA/m]	-260	-382
Intrinsic Coercivity	H_{cj} [kA/m]	-272	-967
Max energy product	$(B\times H)_m$ [kJ/m^3]	36.70	51.70
Temperature coefficient up to 100 °C	dB_r/dT [%/°C]	-0,20	-0,17
	dH_{cj}/dT [%/°C]	+0,32	-0,32

Table I - Magnetic characteristic of the adopted magnets

In Table II the manufacturer technical data concerning the original motor (adopting anisotropic ferrite) are reported.

Permanent magnet	Anisotropic Ferrite
Rated DC voltage	12 V
Rated speed	4000 rpm
Rated torque	0,1 Nm
Rated efficiency	0,75
Number of slots	12
Number of poles	8
Rotor outer diameter	88,2 mm
Rotor inner diameter	83,6 mm
Stator outer diameter	72 mm
Magnet thickness	5 mm
Air gap	0,8 mm

Table II - Characteristics and dimensions of the PM BLDC motor

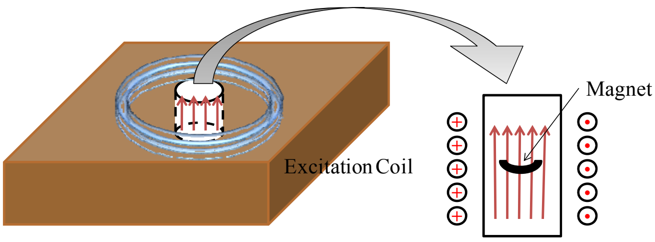

Fig. 2 – Required magnetic circuit for the parallel magnetization

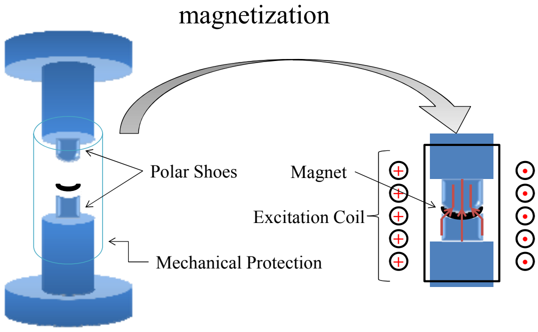

Fig. 3 – Adopted magnetic circuit for the radial magnetization

The aim of this work involves the evaluation of the impact of the magnetization direction on the machine performance [7], [9]. The magnetizations here considered are the parallel and the radial one [11], which present different levels of complexity and required devices.

Parallel magnetization is easy to be obtained directly in air inside the magnetizer coil, without the need of any particular adaptation (Fig. 2); on the other hand radial magnetization requires the adoption of a dedicated magnetic circuit (Fig. 3) realized by the authors in their electromechanical laboratory with a high magnetic permeability material (Fig. 4) [11].

To get equivalent levels in terms of final magnetization, the discharge level of the magnetizer has been set to different values if working in air or with the magnetic circuit.

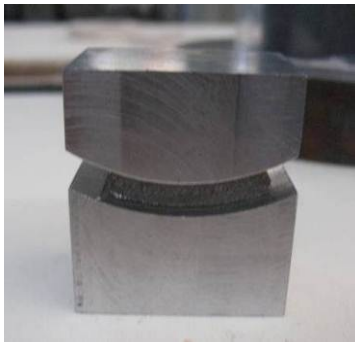
Fig. 4 – Polar shoes around the magnet


Fig. 5 – Magnetized samples: left parallel, right radial

III. Investigation Steps

The analysis of the effects of the different magnetizations on the iron losses in the realized machines adopting bonded magnets will be conducted with the following steps:

- realization of machine prototypes adopting bonded magnets with parallel and radial magnetization [11];
- f.e.m. simulation of the machines [26];
- determination of the simulated flux and voltage waveforms at no load;
- experimental measurement of the voltages with the machine in rotation under no load conditions;
- evaluation of the DC voltage rated value which constitutes the bus voltage for driving the motor through a full bridge with a six-steps commutation;
- evaluation of the different loss contributions [22], [27], [28], [29]:
  - static friction bearings torque and losses
  - mechanical losses due to the rotating movement (ventilation and similar)
  - hysteresis iron losses
  - eddy current iron losses and additional losses
- at the aim an experimental activity has been necessary for the separation of the iron hysteresis losses [30], [31].

A. *Magnetic simulation*

In the following the evaluation of the flux machines is presented for the case of bonded magnets both for radial and parallel magnetization [11]; on the basis of the magnetic simulation results, with the adoption of a derivative procedure, the corresponding e.m.f. waveform and value have been deduced.

From the waveform analysis important information may be deduced: the evaluation of the average value of a single e.m.f. phase, and the harmonic content that can differently influence the iron losses in the two machines.

The simulated flux density distribution of the machine adopting bonded magnet magnets with parallel magnetization is reported in Fig. 6, while in Fig. 7 the same analysis is proposed for the machine adopting bonded magnets with radial magnetization.

In Fig. 8 the comparison of the simulated stator pole fluxes are shown; it has to be observed a maximum flux value a bit higher for the radial case.

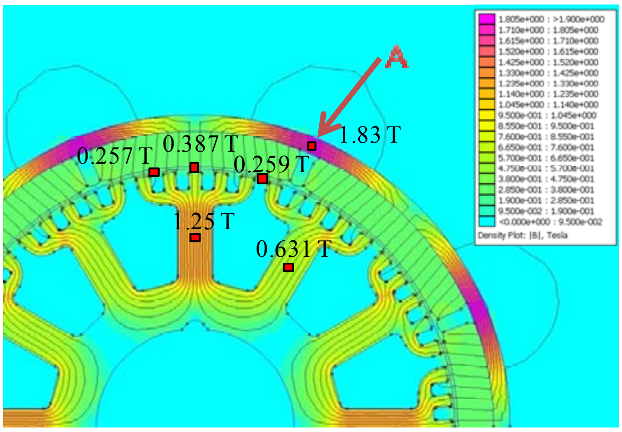

Fig. 6 – Flux density distribution (parallel bonded magnet motor)

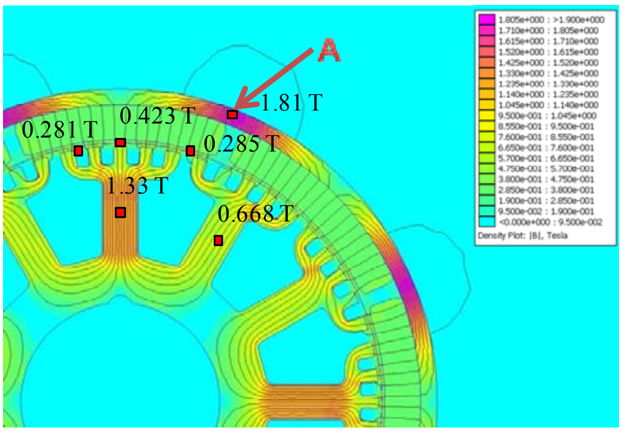

Fig. 7 – Flux density distribution (radial bonded magnet motor)

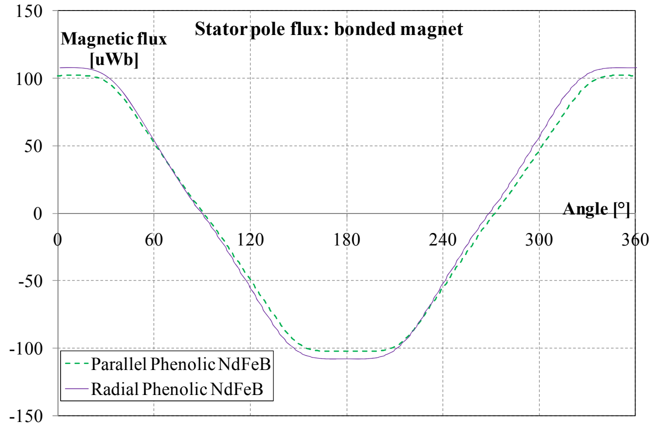

Fig. 8 – Comparison of the simulated stator pole flux

B. *Experimental verification*

The simulation process has been followed and validated with an experimental activity conducted on a properly realized test bench (Fig. 9).

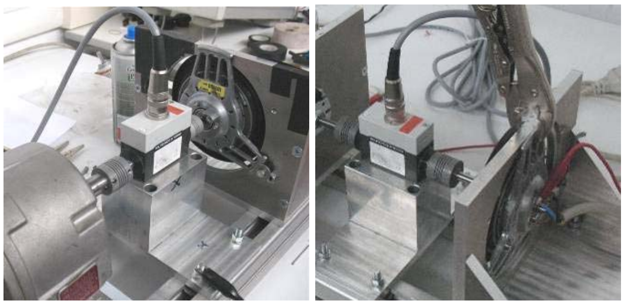
Fig. 9 – Dedicated experimental test bench

The machines under exam have been experimentally tested at the aim of obtaining the necessary data to be compared with the simulations and their consequent validation.

A series of tests allowed to acquire the e.m.f. induced in the open windings of the machines when dragged by an external motor.

The obtained results at the rated speed of 4000 rpm for the parallel and radial magnetized machines are shown in Fig. 10 and Fig. 11: the comparison between the simulated and the experimental values of the e.m.f. is proposed, with a good matching of the results.

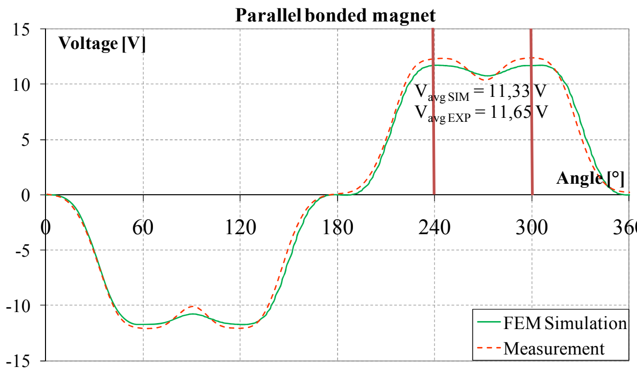

Fig. 10 – Experimental and simulated voltage for parallel bonded magnet motor

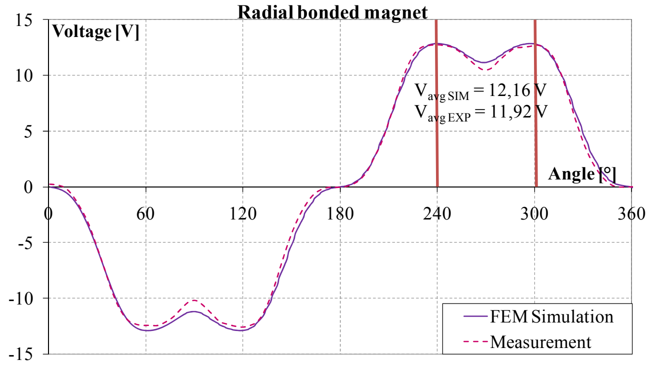

Fig. 11 – Experimental and simulated voltage for radial bonded magnet motor

Such a result shows a good reliability of the magnetic simulation process, which may be useful for other considerations.

C. DC supply voltage determination

The experimental activity carried out to validate the simulation, allows also to evaluate an important quantity for the calculation of the possible rated power of the machine, when used as six-step brushless motor: the possible rated bus DC voltage (as mentioned at the beginning of this Section). It may be deduced from the average voltage value evaluated on the 60 degrees concerning the interval of connection to the DC bus by the bridge commutation.

From the experimental results, at 4000 rpm, the following voltages are obtained:

$V_{avg\ PARALLEL} = 11{,}65$ V

$V_{avg\ RADIAL} = 11{,}92$ V

D. Losses evaluation

In order to carry out a quantitative comparison under the point of view of the energetic performances, it is necessary to provide a series of special experimental phases.

The losses can be divided into two categories: the ones depending on the magnetic flux and the ones depending on mechanical type frictions not depending on the magnetic phenomena.

The basic measurement activity was performed with the bench of Fig. 9 by dragging the machine through the interposition of a special transducer; it allowed to obtain the value of torque, input mechanical power and speed. All the measured voices are related to the machines working with no load.

The experimental phase may be summarized as follows.

1. At first the total torque T_0 and power P_0 have been measured; the results are reported in Fig. 12.

2. The torque value at zero speed gives the amount depending on the bearings static friction added to the average value depending on the magnetic hysteresis. By subtracting such voice, the remaining quantity contains the torque contributions which depend on the dynamic frictions (such as the ventilation effect) and on the eddy currents.

A dedicated measurement on a special prototype adopting non magnetized magnets, provided the rotation friction loss contribution at 4000 rpm equal to 2,0 W.

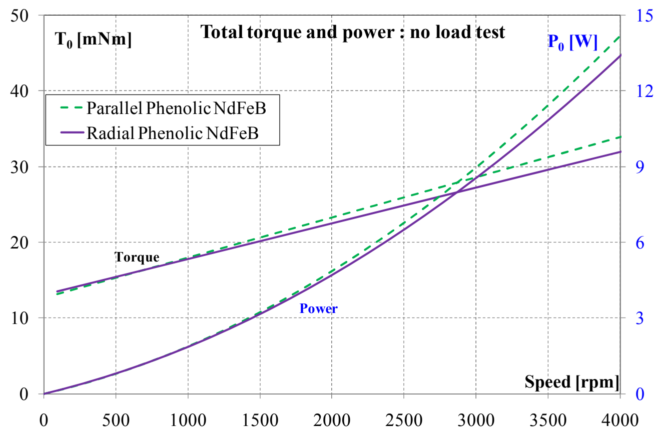

Fig. 12 – Total torque and power measured at no load

3. Through the described process, the power losses due to the eddy currents are evaluated (Fig. 13).

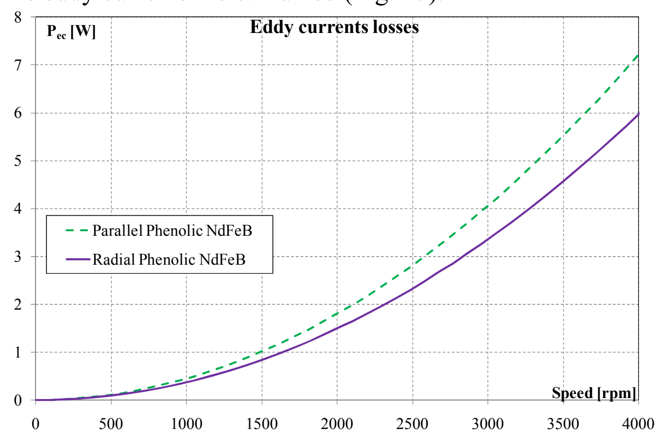

Fig. 13 – Eddy currents losses

In order to obtain a complete knowledge of the different loss contributions it has been necessary to proceed at the separation of the bearing static torque from the voice depending on the hysteresis.

E. Hysteresis losses (≈ zero speed tests)

The machine stator poles are subjected to alternating magnetization giving origin to torques due to hysteresis phenomena; they cannot be distinguished, following the traditional methodologies, from the static contribution due to the bearings static friction.

To measure the torque vs. angle values depending both on the bearing static friction and on the hysteresis phenomena, the shaft motor has been driven at very low, regular and constant speed; the interposed torque sensor allows to measure the mentioned voices and its average value on one complete revolution.

A series of tests at a speed near to zero have been realized to deduce the angle dependence of the torque both for motors with mounted magnets without magnetization and for motors adopting the two types of magnetization process under exam.

That allows to separate the static friction contribution from the torque due to the hysteresis phenomena: in such a way the friction and the hysteresis torque have been successfully separated.

The torques represented in Fig. 14 and Fig. 15 present an average value on a complete revolution composed by the bearing contribution and the hysteresis average value; the high frequency oscillating component, depending on the reluctance modulation, has average value equal to zero. Its contribution can be filtered and insulated from the other two: in Fig. 16 and Fig. 17 the resulting torque contributions having periodicity equal to a mechanical revolution (and hence due to the bearing static friction and to the hysteresis) are reported for parallel and radial bonded magnet.

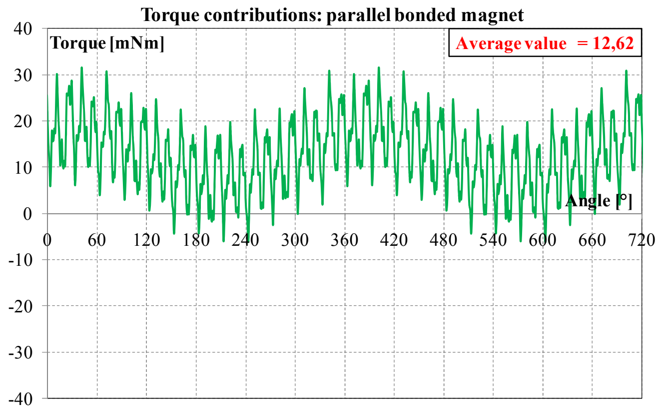

Fig. 14 – Torque waveform for parallel machine vs. shaft position

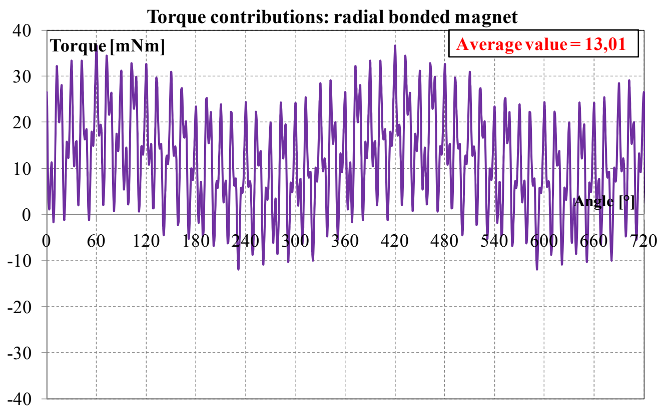

Fig. 15 – Torque waveform for radial machine vs. shaft position

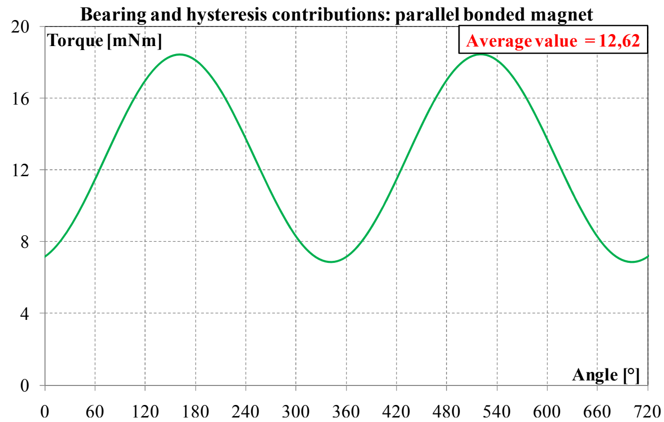

Fig. 16 – Hysteresis torque evaluation T_{hys} (parallel bonded magnet)

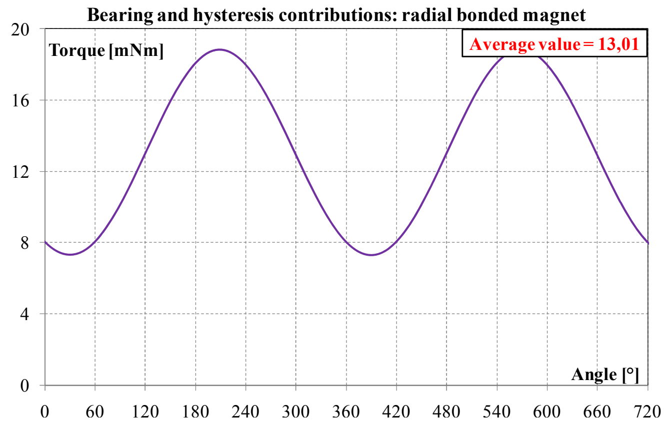

Fig. 17 – Hysteresis torque evaluation Thys (radial bonded magnet)

The separation between hysteresis and bearing contributions has been made possible with tests on a machine equipped with a “non magnetized” rotor: in such conditions, with the same mechanical structure and inertia, the losses in the material are obviously equal to zero and as a result only the bearing friction component can be evaluated, as shown in Fig. 18.

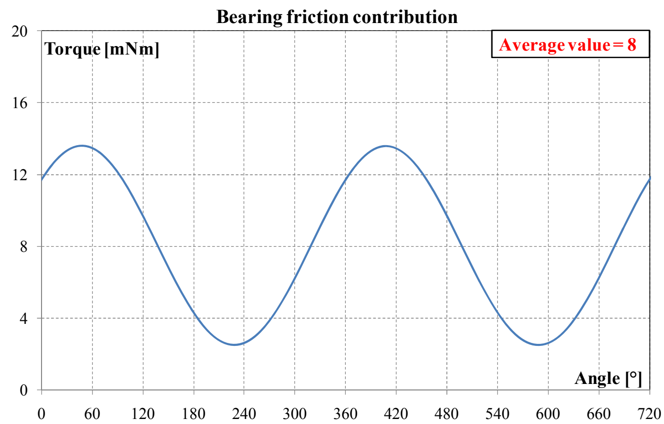

Fig. 18 – Bearing torque evaluation T_{bear}

From the average values of the torques of Fig. 16 and Fig. 17, the static bearing torque T_{sb} = 8×10^{-3} Nm must be subtracted to obtain the hysteresis torque contributions for the two considered magnets:

$T_{hys\ parallel\ bonded} = 4{,}62\times10^{-3}$ Nm
$T_{hys\ radial\ bonded} = 5{,}01\times10^{-3}$ Nm

Is it then possible to evaluate the hysteresis losses in dependence of the speed (frequency), as shown in Fig. 19.

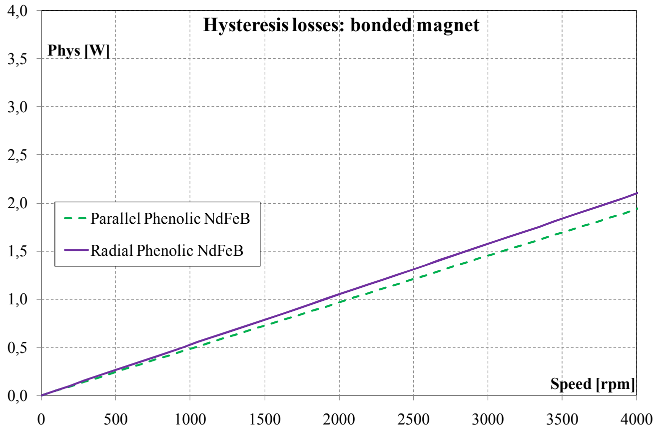

Fig. 19 – Hysteresis losses evaluation P_{hys} : comparison between parallel and radial bonded magnets

IV. Results Evaluation

Different machines have been assembled to perform the comparison between the effects of the different kinds of magnetization. The experimental activity allowed to reach, as important result, the separation of the different loss contributions, with consequent evaluation of the energetic behaviour of the machines in relationship with the different magnetizations.

The analysis is performed under the hypothesis of maintaining the rated current of the original machine (4,6 A) and the related stator joule losses (1,9 W) as fixed value.

Power evaluation

- allowable input power P_{inR} for the case of radial magnetization:
  $P_{inR} = V_{avg\ RADIAL} \times I_{rated} = 11{,}92\times4{,}6 = 54{,}83$ W
- allowable input power P_{inP} for the case of parallel magnetization:
  $P_{inP} = V_{avg\ PARALLEL} \times I_{rated} = 11{,}65\times4{,}6 = 53{,}59$ W

For an evaluation of the allowable output power P_{outR} and P_{outP} the different loss contributions at the speed of 4000 rpm have to be considered.

The following values are valid for *both cases*:

Bearing losses	3,4	W
Fluidic friction losses	2,0	W
Joule losses	1,9	W
Total basic losses	7,3	W

As regards the iron losses, the following data have been obtained:

radial magnetization:

Hysteresis losses	2,10	W
Eddy current losses	5,97	W
Total Radial iron losses	8,07	W

parallel magnetization:

Hysteresis losses	1,93	W
Eddy current losses	7,21	W
Total Parallel iron losses	9,14	W

From the above elements, the following values for the obtainable output power are deduced:

$P_{outR} = P_{inR} - \Sigma losses_R = 54{,}83 - (7{,}3+8{,}07) = 39{,}46$ W

$P_{outP} = P_{inP} - \Sigma losses_P = 53{,}59 - (7{,}3+9{,}14) = 37{,}15$ W (-6%)

V. Final Considerations

1) Even if the present analysis has to be considered of general character, it provides some clear information; if we consider as reference data the output power evaluated for the original motor (ferrite magnets with radial magnetization) which results of 34,67 W, the adoption of the considered bonded magnets allows an interesting power increment, respectively of 14 % for the radial solution and 7 % for the parallel one.
2) The adoption of the parallel magnetization magnets brings to a derating of the obtainable output power from the same electromechanical structure with respect to the one adopting magnets providing a radial magnetization. The obtained derating value of a few percent has to be considered representative enough.
3) The energetic performance is basically affected by the "iron losses" value; it is interesting to observe that in case of radial magnetization, in spite of a bigger stator pole flux density, the total losses of magnetic type result lower, giving origin to the described better performance. If the hysteresis losses amount follows the mentioned flux density value, that is not true for the losses called in this paper as "eddy current losses". That is depending on the fact that additional losses due to "eddy currents" are present not only in the stator laminated structure; for instance, if we consider the point "A" of the rotor ring (Fig. 6 and Fig. 7) during the rotation it presents for the local flux density:
   - an oscillation from 1,83 T to 1,8 T during the rotation of 45 degrees (at a frequency of about 550 Hz) for the case of parallel magnetization;
   - no practical oscillation during the rotation is affecting the maximum value of the flux density in the rotor ring (about 1,81 T) for the case of radial magnetization.

   Similar considerations may be deduced for the different points of the rotor ring.

Such a type of “additional losses” results great enough to make the total so called “iron losses” bigger for the case where the stator presents lower flux density.

4) All the performed activities and the reported analysis allow to establish that the output rated power reduction due to the parallel magnetization is limited to a percentage which may be considered small; in fact we have to consider the advantages of the adoption of the easier parallel magnetization process, when the magnets are subjected to the magnetization action before the introduction in the motor, as it is verified in a large number of applications.

Finally it is interesting to underline that, with reference to Fig. 14 and Fig. 15, it is well evident the presence of torques depending on variation of the magnetic reluctance caused by the rotor displacement [14], [32], [33]; but such components give origin to an average value equal to zero and then have not been considered in this paper because of the aim concerning energetic considerations. For the type of motor under exam, the mentioned phenomenon is not of secondary importance but without energetic effect and will be considered in investigation phases having different finalities.

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VIII. Biographies

Luca Ferraris Luca Ferraris received the Laurea degree in electrical engineering from the Politecnico di Torino, Italy in 1992. He joined the Department of Electrical Engineering of the Politecnico di Torino in 1995, and he is now an associate professor of Electrical Machines and drives. His research interests are the energetic behavior of machines, electrical traction, electromagnetic compatibility, and renewable energies. He has published more than 40 technical papers in conference proceedings and technical journals. Currently he coordinates the experimental activities of the Electric and Electromagnetic Laboratories.

Paolo Ferraris received his Master’s degree in 1963 from Politecnico di Torino, Italy. In the same year he started his academic career in the same University, where is currently Full Professor of Electrical Machines and Drives. He covered the rule of Director of Department of Electrical Engineering in different periods for a total of about 15 years. Past President of the Electrical Machines Group inside the National Research Council (CNR) and of European Power Electronics Association (EPEA, Brussels), devoted his research activity in the field of Electromagnetic Machines and related Energetic problems, Power Electronic Converters, and Renewable Energy problems, including Electric Vehicles. He published more than 100 papers on such items and currently bases his activity inside the Alessandria site of the Politecnico di Torino where spent the last 15 years in the foundation of the site, local full management, research coordination and didactic responsibility.

Emir Pošković was born in Sarajevo in the Bosnia and Herzegovina, SFR Yugoslavia on September 30, 1981. He studied and graduated from the Polytechnic of Turin, where he received B.S. and M.Sc. degree in electrical engineering in 2006 and 2008 respectively. His employment experience included the Polytechnic of Turin, research center of Polytechnic of Turin at the Alessandria (CESAL). His special fields of interest included electrical machines, alternative and renewable energy.

Alberto Tenconi received a master’s degree and doctorate in electrical engineering from the Politecnico di Torino in Italy in 1986 and 1990, respectively. From 1988 to 1993, he was with the Electronic System Division of the FIAT Research Center. He then joined the Department of Electrical Engineering at the Politecnico di Torino, where he is currently full professor. His fields of interest are advanced machine and drive design and he has published more than 130 papers in international journals and international conference proceedings. He is a Senior Member of the IEEE and Associate Editor for the IEEE Transactions on Industrial Electronics.